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Development of a groundwater quality baseline in the Abu Dhabi Emirate

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Development of a groundwater quality baseline in the Abu Dhabi Emirate

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Abstract

Understanding the suitability of groundwater resources for domestic, agricultural, and industrial uses in hyper-arid environments requires a systematic and spatially representative baseline. This study establishes such a baseline for the Abu Dhabi Emirate, targeting zones with directly usable groundwater defined by Total Dissolved Solids (TDS) ≤ 15,000 mg/L. A grid-based sampling campaign covering 39 cells in the Eastern Region and 60 cells in Al Dhafra was implemented, with wells selected by land-use type (agricultural, forestry, urban, industrial, and special sites). Groundwater samples were analysed for major ions, trace elements, volatile organic compounds, pesticides, pharmaceuticals, microbiological indicators, and environmental isotopes (δ^2H, $\delta^{18}O$, ^3H, $\delta^{13}C$, ^{14}C, $\delta^{15}N$) by ISO 17025-accredited laboratories. Significant spatial variability in groundwater quality was observed. Salinity ranged from 473 to 46,000 mg/L TDS, with fresher waters concentrated near the Oman border. Na–Cl–SO_4 and Na–Ca–Cl–SO_4 were the dominant water types. Boron and chromium exceeded EAD (2017) guideline values in 141 and 121 samples respectively, with distributions suggesting predominantly geogenic origins. Pesticides were detected in 37 wells and the contrast agent amidotrizoic acid in five wells, confirming localised anthropogenic influence. Tritium was detected in 35 samples and ^{14}C activities of 14.9–89.8 pmc yielded uncorrected residence times of ~1,000–20,000 years, indicating that most groundwater is sub-modern to fossil. The study proposes a tiered monitoring programme combining routine sampling with comprehensive five-year resurveys and recommends further investigation of geogenic trace-element sources and modern recharge pathways.

Keywords Groundwater quality · Hydrogeochemistry · Stable isotopes · Tritium · Arid aquifer · Water quality index · Abu Dhabi · United Arab Emirates

1 Introduction

Groundwater is an indispensable resource in the Abu Dhabi Emirate, playing a pivotal role in sustaining domestic, agricultural, and industrial activities. The hyper-arid climate of the region — characterised by low precipitation (~60–100 mm yr^{-1}) and high potential evaporation — places immense pressure on groundwater resources, making their management and protection a critical concern. Groundwater currently accounts for about 61 % of total water demand in the Emirate, with desalination (29 %) and recycled water (10 %) supplying the remainder; irrigation for agriculture,

forestry, amenity planting, and landscaping together account for more than 95 % of total annual abstraction [1].

With a rapidly growing population and expanding economic base, the Emirate faces compounded pressures on the quality and availability of its groundwater. The establishment of a comprehensive groundwater quality baseline is therefore a strategic step, providing a reference against which long-term changes can be detected and informing evidence-based management. Previous studies in the UAE [2–5] have characterised selected aquifer units and highlighted salinity distribution, carbonate dissolution, and evidence of limited recharge, but an Emirate-wide, multi-parameter, isotopically-constrained baseline has been lacking.

In neighbouring arid settings, grid-based sampling combined with isotopic tools has been shown to resolve both geogenic and anthropogenic drivers of groundwater chemistry [6–8]. Studies across the Arabian Peninsula have documented widespread trace-element enrichment in groundwater from geogenic sources [9,10], while Holocene and Late Pleistocene palaeo-recharge has been demonstrated through $\delta^{2}H$, $\delta^{18}O$, and ^{14}C signatures [11–13]. Anthropogenic pressures — including fertiliser leaching, pesticide application, and wastewater-borne pharmaceuticals — have also been reported as emerging threats in similar hyper-arid aquifers [14].

Despite the body of work cited above, few studies have integrated the full range of hydrogeochemical, trace-element, organic-contaminant, microbiological, and multi-isotope indicators at the scale of an entire Emirate, using a spatially representative, land-use-stratified grid design. The present study addresses this gap. The specific objectives are to: (i) characterise the baseline hydrochemistry of groundwater in the usable-salinity domain (TDS ≤ 15,000 mg/L) of the Abu Dhabi Emirate; (ii) quantify the occurrence of anthropogenic compounds and microbiological indicators in relation to land use; (iii) constrain recharge processes and groundwater residence times using environmental isotopes; and (iv) translate the results into use-specific Water Quality Indices (WQI) for domestic, irrigation, and livestock applications, thereby supporting a long-term Groundwater Quality Monitoring (GWQM) Network. The study distinguishes the Eastern Region and Al Dhafra as two hydrogeochemical sub-units with contrasting flow, recharge, and salinity regimes (Fig. 1).

Despite the valuable contributions of earlier UAE-focused studies, a clear scientific gap remains. Rizk and Alsharhan [2] provided a broad overview of national water resources but predated systematic isotopic characterisation; Imes and Wood [8] and Wood [11] constrained palaeo-recharge and solute evolution through stable isotopes and ^{14}C in the western dune belt, yet without integrating trace-element geochemistry or anthropogenic markers; Murad et al. [3,10] and Murad and Krishnamurthy [12] provided detailed hydrogeochemical and isotopic interpretations of the carbonate aquifer in the south-eastern Al Ain area; and Sherif et al. [4] modelled natural recharge from rainfall across the UAE, but did not include in-situ water-quality indicators. What is currently missing is an integrated, spatially representative, multi-parameter and isotopically constrained baseline covering both geogenic and anthropogenic signatures at the scale of the entire Abu Dhabi Emirate. The present study addresses this gap by answering three specific research questions: (i) What is the relative contribution of geogenic and anthropogenic sources to the observed trace-element guideline exceedances, particularly for boron, chromium, selenium, and molybdenum? (ii) Does modern recharge reach the usable-salinity aquifers across the Emirate, at what spatial density, and to what extent does it co-occur with anthropogenic contaminants (pesticides, pharmaceuticals, microbiological indicators)? (iii) How do the Eastern Region and Al Dhafra differ in recharge regime, residence time, and use-specific water-quality indices, and what does this imply for a tiered long-term monitoring programme? The novelty of this work therefore lies in combining, for the first time at the Emirate scale and within a single land-use-stratified sampling design, the full hydrogeochemical suite (major ions and trace elements), a screening of anthropogenic markers (VOCs, pesticides, pharmaceuticals, microbiological indicators, dissolved gases), and a comprehensive environmental-

isotope panel (δ^2H, $\delta^{18}O$, ^3H, $\delta^{13}C$, ^{14}C, $\delta^{15}N$) — elements that earlier regional studies [2–4,8,10–12] addressed only in isolation or in smaller sub-areas — and translating the integrated results into use-specific Water Quality Indices that directly inform groundwater management policy in the Emirate.

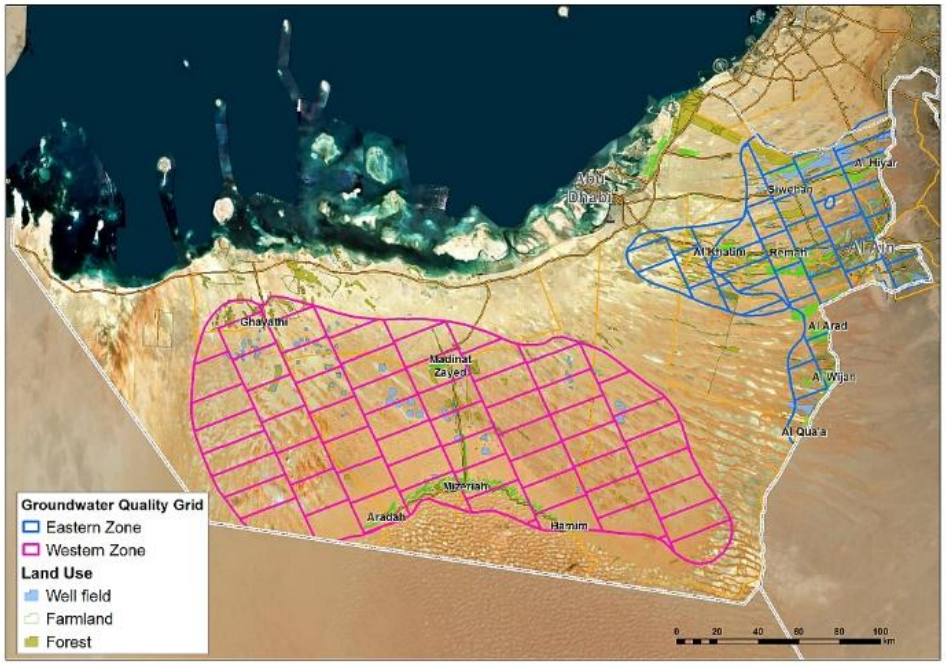


Fig. 1 Location map of the study area with the groundwater-quality sampling grid in the Abu Dhabi Emirate, showing the Eastern Region (39 cells) and Al Dhafra (60 cells).

2 Methods

The methodology was designed to yield a reproducible, spatially representative assessment of groundwater resources in zones with directly usable salinity (TDS ≤ 15,000 mg/L). The study was structured in three phases: (i) initiation and sampling design; (ii) collection and analysis of groundwater samples; and (iii) data interpretation, indexing, and reporting.

2.1 Sampling design

A grid-based sampling design was adopted to capture the spatial variability of groundwater quality. The study area was partitioned into 10 km × 10 km grid cells, yielding 39 cells in the Eastern Region and 60 cells in Al Dhafra (Fig. 2). Within each cell, wells were selected based on primary and secondary land-use types including residential, agricultural (farm, forestry), and industrial areas. Special land-use categories — petrol stations, waste-handling sites, and wastewater-related infrastructure — were included to capture potential anthropogenic impacts (Fig. 3, Fig. 4).

2.2 Identification of sampling wells

Candidate wells were drawn from the EAD Well Inventory database (~120,000 wells). Operational wells with sampling access — defined as having a bypass on the discharge pipe or a point at which a sample could be drawn at the pipe outlet — were prioritised (Fig. 5, Fig. 6). Only wells located within the relevant land-use polygon or within a 500 m buffer were retained (Fig. 7, Fig. 8). Back-up wells were identified for cases in which the primary well could not be sampled for operational reasons (Fig. 9, Fig. 10). Where no operational wells were available within a cell, idle wells were sampled using a

dedicated submersible pump. Purging was continued until field parameters (electrical conductivity, pH, temperature, redox potential) stabilised within ±5 % over three successive readings.

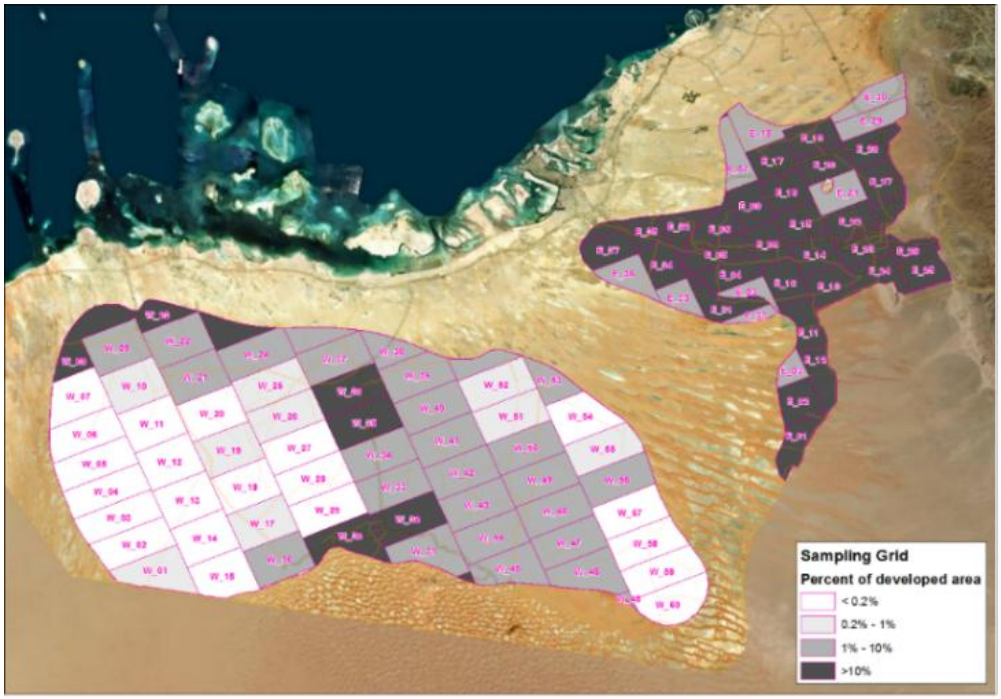


Fig. 2 Sampling grid showing the percentage of total developed land use within each grid cell.

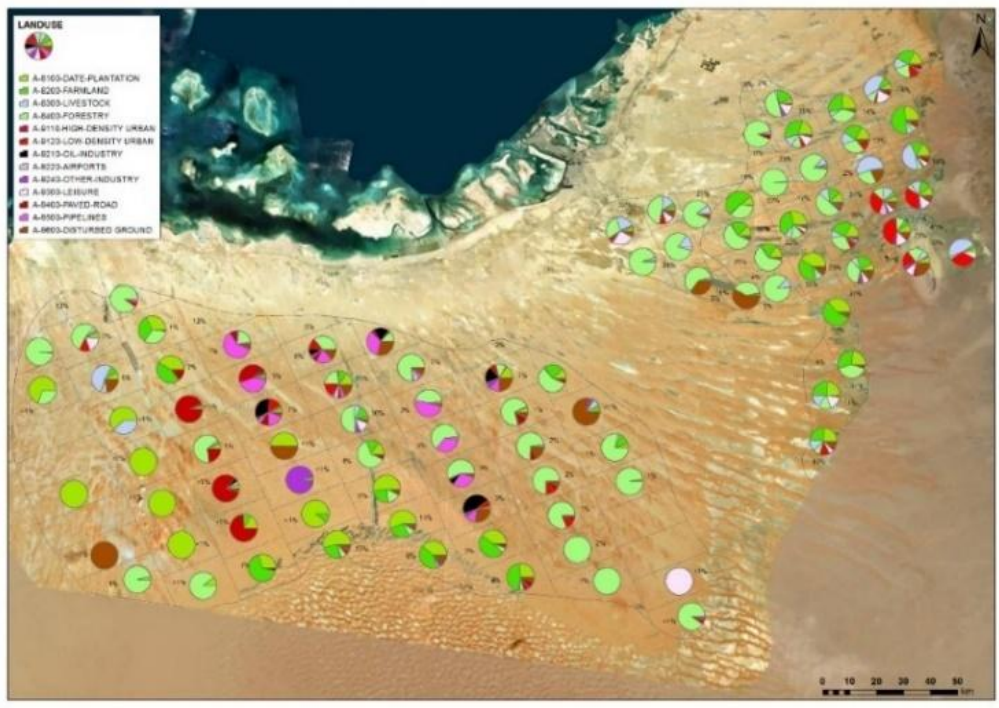


Fig. 3 Percentage of developed land-use types per grid cell, disaggregated by primary land-use class.

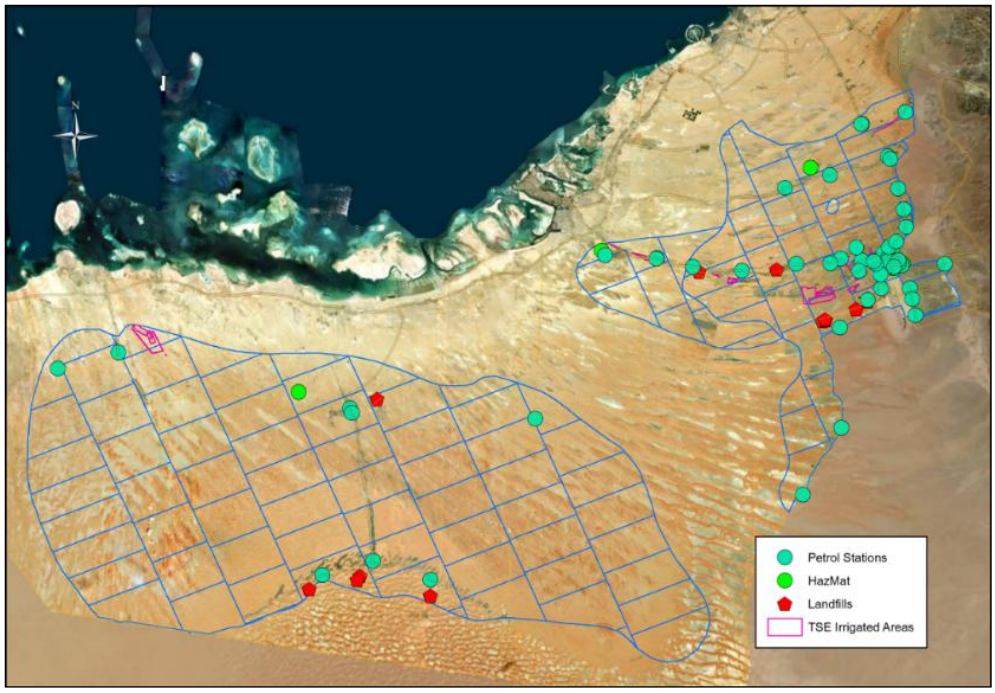


Fig. 4 Special land-use locations (petrol stations, waste-handling sites, and wastewater-related infrastructure) within the sampling grid.



Fig. 5 Splitting of developed areas by the cells of the groundwater-quality sampling grid.

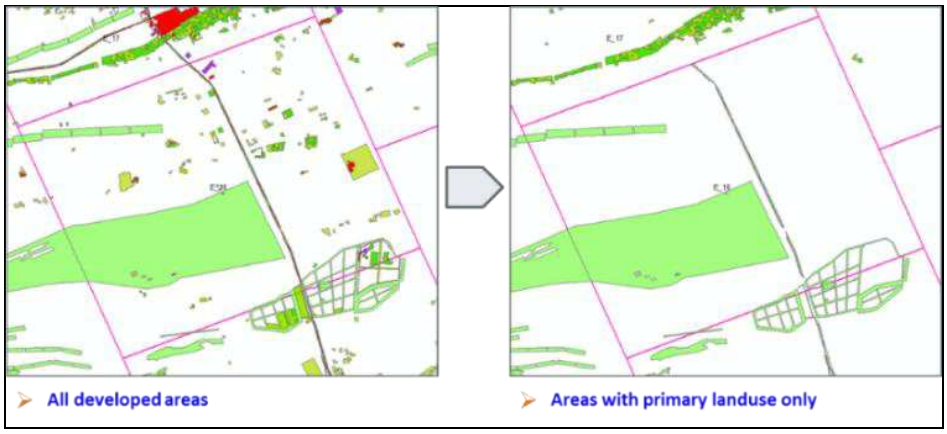


Fig. 6 Selection of primary land use.

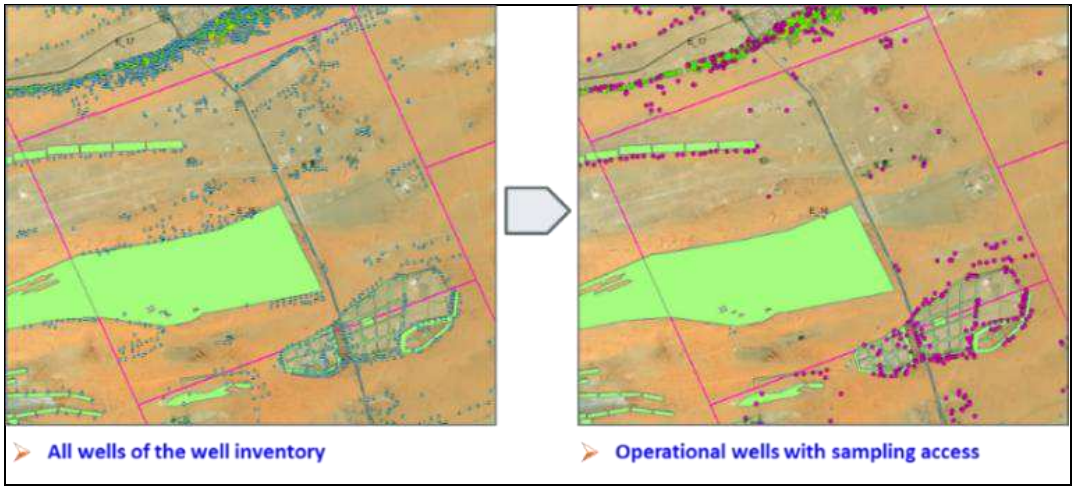


Fig. 7 (left) All wells imported from the Well Inventory Project and (right) wells with sampling access.

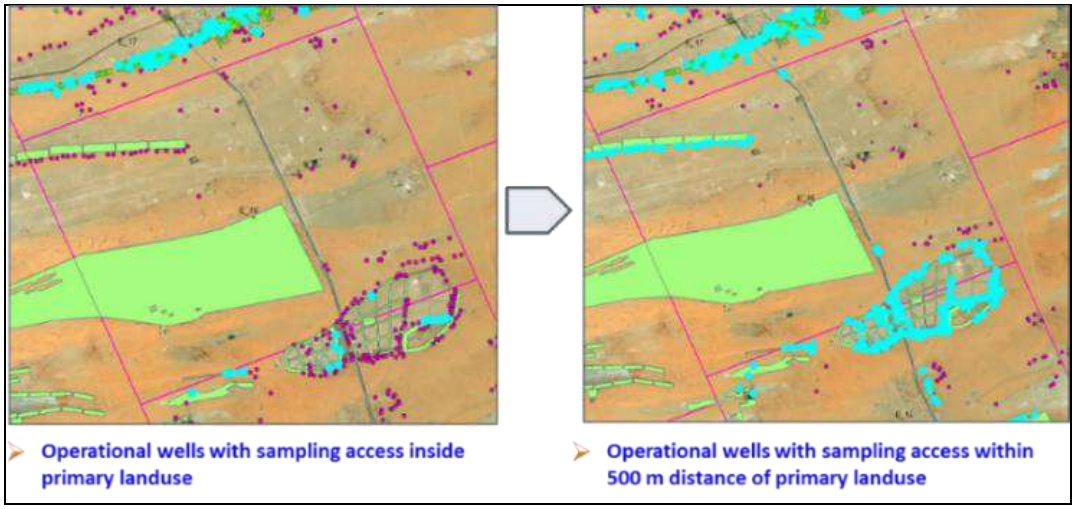


Fig. 8 Selection of operational wells with sampling access (left) within the primary land-use polygon and (right) within a 500 m distance of the polygon.

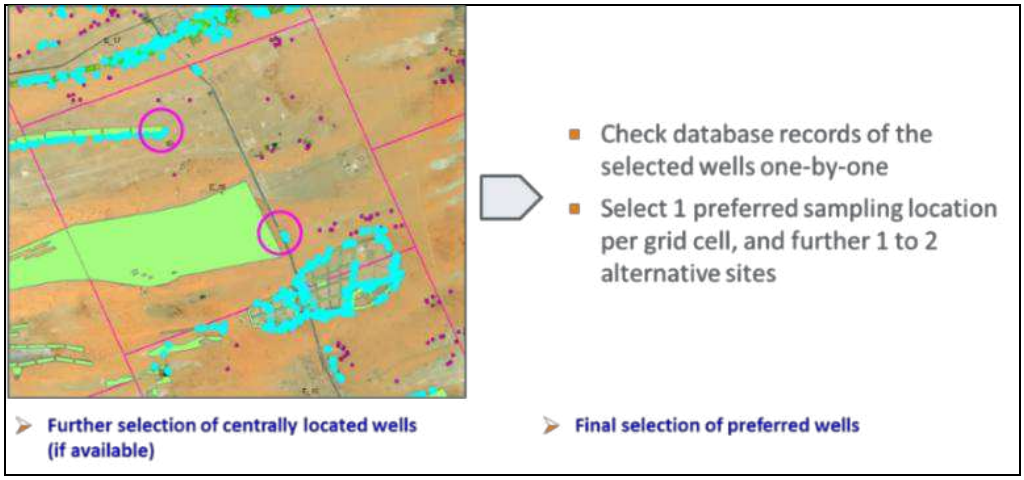


Fig. 9 Selection of back-up wells in case primary wells could not be sampled.

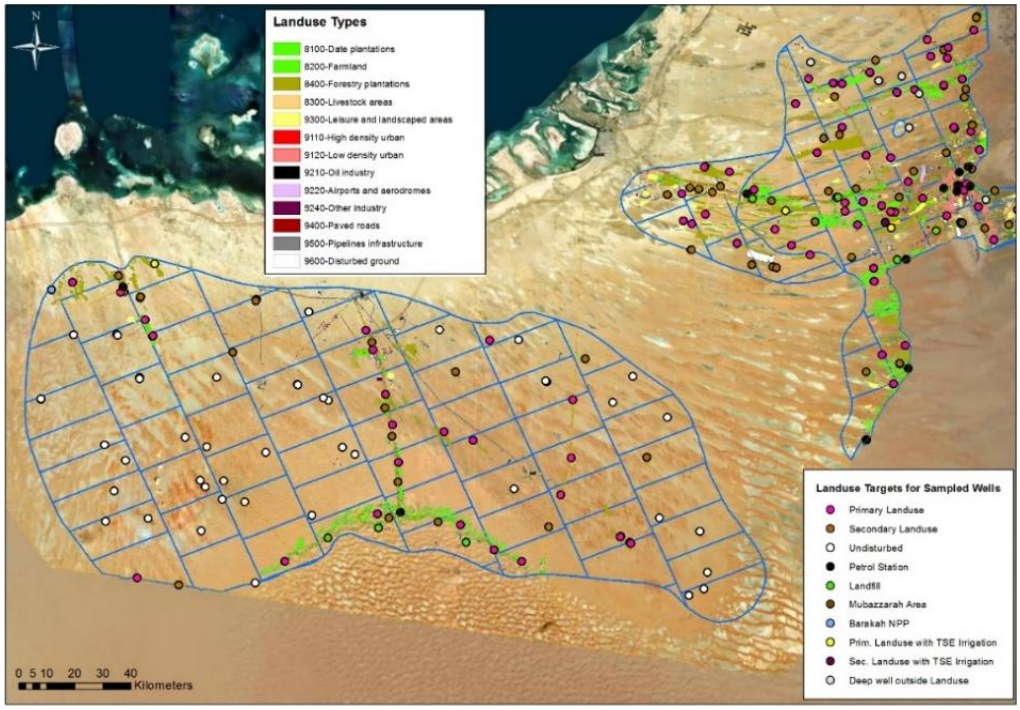


Fig. 10 All wells selected for sampling across the Eastern Region and Al Dhafra.

2.3 Analytical framework

Groundwater samples were analysed for a comprehensive set of parameters covering natural and anthropogenic influences. Major ions (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, HCO_3^{-}) were determined by ion chromatography and titration. Trace elements were quantified by ICP-MS. Volatile organic compounds (VOCs) were analysed by purge-and-trap GC-MS, with Toluene-d8 and 4-Bromofluorobenzene as surrogates. Pesticides were determined by GC-MS with Terphenyl-d14 as surrogate. Pharmaceuticals (carbamazepine, ibuprofen, diclofenac, amidotrizoic acid) were quantified by LC-MS/MS. Microbiological indicators (total coliforms, faecal coliforms,

Escherichia coli, and enterococci) were enumerated by membrane filtration following ISO 9308-1 and ISO 7899-2. Stable water isotopes (δ^2H, $\delta^{18}O$) were measured by cavity ring-down spectroscopy and reported against V-SMOW; tritium (^3H) was measured by low-level liquid scintillation counting following electrolytic enrichment; $\delta^{13}C$ and ^{14}C were measured on dissolved inorganic carbon by accelerator mass spectrometry; $\delta^{15}N$ in nitrate was determined after denitrifier conversion and isotope-ratio mass spectrometry. Dissolved gases (CH_4, N_2, O_2, CFCs, SF_6) were measured by GC with appropriate detectors. All analyses were performed by ISO 17025-accredited laboratories (SGS Gulf Limited for general hydrochemistry and trace elements; Hydroisotop GmbH for environmental isotopes and gases). Quality assurance included procedural blanks, field blanks, field and laboratory duplicates, certified reference materials, and the calculation of charge-balance errors for every sample (only samples with $|CBE| \leq 5$ % were retained for interpretation).

3 Results and Discussion

This section presents the hydrogeochemical, trace-element, anthropogenic, and isotopic findings of the baseline survey and interprets them against regional literature and management-relevant guideline values.

3.1 General hydrochemistry

3.1.1 Basic parameters and salinity classes

Plausibility checks comparing laboratory and field measurements of electrical conductivity (EC), pH, and bicarbonate showed good agreement, with minor deviations in pH attributable to post-sampling equilibration (Fig. 11a, Fig. 11b). For the interpretation below, laboratory EC and bicarbonate values and field pH values were used. EC correlated strongly with laboratory TDS (Fig. 12), providing both a quality check and the basis for salinity classification following the UAE scheme. The encountered salinity classes were: fresh (n = 12), slightly brackish (n = 34), medium brackish (n = 23), strongly brackish (n = 18), slightly saline (n = 52, split into two sub-classes of n = 31 and n = 21), and strongly saline (n = 6). Average TDS/EC ratios per class ranged from 0.57 to 0.77, consistent with expectations for Na–Cl–SO_4 dominated waters.

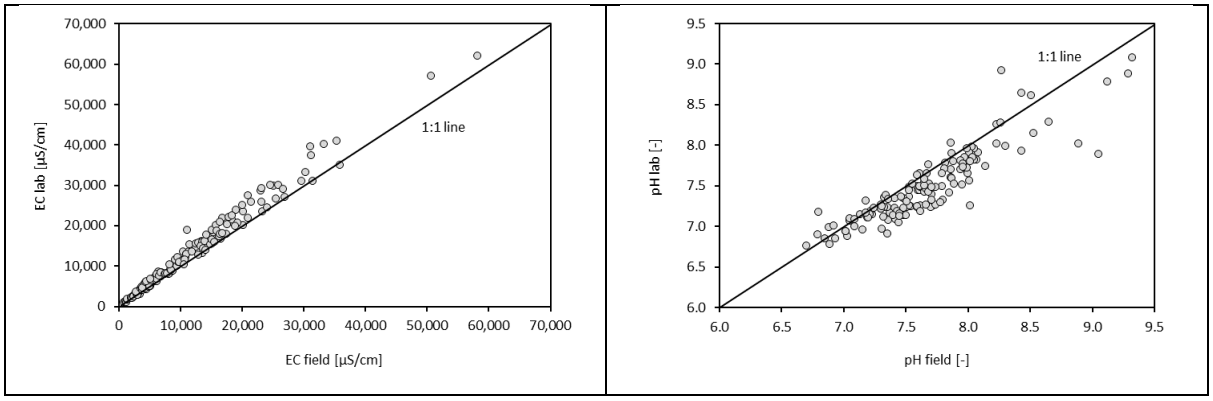


Fig. 11 Scatter plots showing the relation between (a) EC lab and EC field; (b) pH lab and pH field.

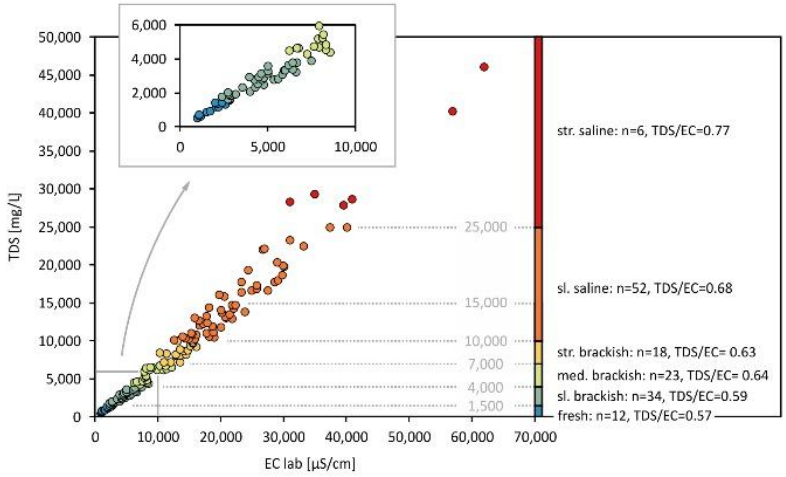


Fig. 12 Scatter plot showing the relation between TDS and EC (laboratory).

Table 1 summarises descriptive statistics for the main field and laboratory parameters and indicates the number of exceedances of EAD (2017) guideline values (n > GLV) for domestic non-potable use, irrigation, and livestock watering. Major-ion concentrations varied systematically with salinity (473–46,000 mg/L TDS), and spatial patterns mirrored those of TDS. The dominant chemical water type across the dataset was Na–Cl–SO_4 (n = 69), followed by Na–Ca–Cl–SO_4 (n = 22) and Na–Cl (n = 18) (Table 2). Piper plots, classified by salinity class, revealed a shift from a more balanced anion composition in fresh waters (occasionally HCO_3-dominated) toward SO_4 and Cl dominance with increasing salinity, culminating in Cl-dominance in strongly saline waters (Fig. 13). This trend is

consistent with carbonate dissolution at the early stage of groundwater evolution and subsequent concentration by evapotranspiration and mixing with residual saline waters [15,16].

Table 1 Statistical summary for selected physico-chemical parameters and number of exceedances (n > GLV) of EAD (2017) guideline values for domestic non-potable use, irrigation, and livestock watering. b.d.l., below detection limit.

Parameter	Min	Mean	Max	Dom. use	n > GLV	Irr.	n > GLV	Livestock	n>GLV
EC field [µS/cm]	835	12,430	58,200						
T field [°C]	24.5	32.7	47.4						
pH field [–]	6.7	7.7	9.3						
Turbidity [NTU]	0.0	2.2	23.0	5	22				
Alkalinity [mg/L $CaCO_3$]	45	112	540						
Bicarbonate [mg/L]	54.9	137	659						
TDS [mg/L]	473	9,449	46,000	1,000	139				
Calcium [mg/L]	8	450	1,447						
Magnesium [mg/L]	6	259	1,565						
Sodium [mg/L]	105	2,228	12,090						
Potassium [mg/L]	5.3	54.2	213						
Chloride [mg/L]	127	3,714	20,677	200	143	700	121		
Sulphate [mg/L]	1.1	1,741	5,535						
Fluoride [mg/L]	b.d.l.	1.1	7.8	0.4	55	1.0	51	2	39
Nitrate [mg/L]	b.d.l.	76.2	474	45	76				
Nitrite [mg/L]	b.d.l.	0.2	14.7	3	2			10	1

n > GLV is the number of cases in which the guideline value (GLV) is exceeded.

Table 2 Encountered chemical water types and their frequencies in the sampled wells (n = 145).

Water type	Frequency	Water type	Frequency
Na–Cl–SO_4	69	Ca–Na–Cl–SO_4	1
Na–Ca–Cl–SO_4	22	Mg–Na–Ca–Cl–SO_4	1
Na–Cl	18	Mg–Na–Cl–SO_4	1
Na–Mg–Cl–SO_4	14	Na–Ca–Mg–Cl–SO_4	1
Na–Ca–Cl	4	Na–Ca–Mg–SO_4–Cl	1
Na–Mg–Cl	3	Na–Mg–Ca–Cl–SO_4	1
Na–Mg–SO_4–Cl	3	Na–Mg–Ca–SO_4–Cl	1
Na–Mg–Cl–HCO_3–SO_4	2	Na–Mg–HCO_3–Cl–SO_4	1
Na–Mg–Cl–SO_4–HCO_3	2		

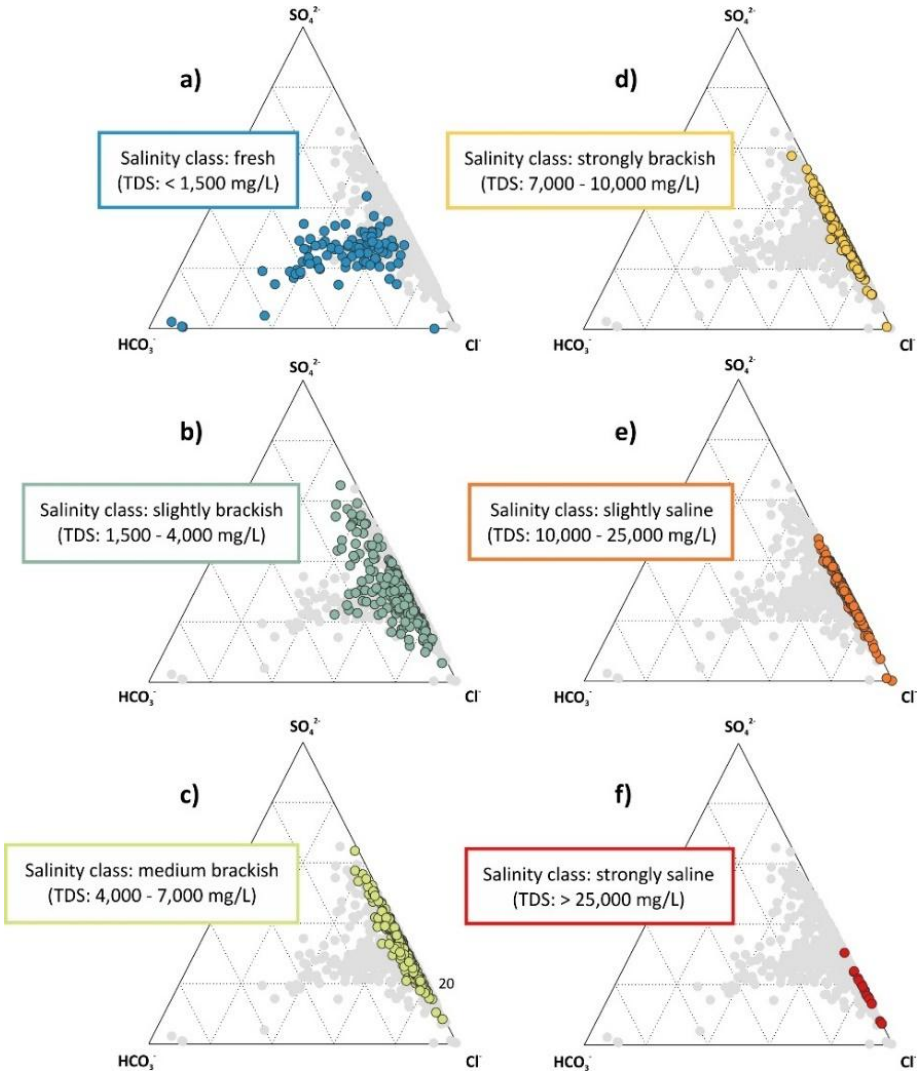


Fig. 13 Compilation of anion triangles from the Piper plots across all salinity classes.

Fluoride and nitrate, although not major anions, exhibited substantial absolute concentrations. Fluoride (mean 1.1 mg/L; maximum 7.8 mg/L) exceeded the EAD guidelines for domestic use (55 cases), irrigation (51), and livestock (39). Nitrate (mean 76 mg/L; maximum 474 mg/L) exceeded the domestic guideline (45 mg/L) in 76 samples, with elevated levels concentrated in the agricultural Liwa crescent. Both fertiliser leaching and natural accumulation since Holocene recharge are plausible contributors [17]. Box plots by land use confirmed higher nitrate in farms than in urban areas (Fig. 14). A Pearson correlation matrix (Fig. 15) showed strong positive correlations among major ions and TDS ($R = 0.76–0.99$, $p < 0.01$) but not with bicarbonate — consistent with carbonate solubility controls — nor with fluoride, bromide, and nitrate, whose distribution is controlled by aquifer lithology and anthropogenic loading rather than by bulk salinity.

3.1.2 Trace elements

QA/QC for trace elements, based on duplicates and certified reference materials, showed good agreement with nominal values. Table 3 summarises the trace-element statistics and guideline exceedances. Arsenic exceeded the domestic guideline (18 µg/L) in three farm wells (28, 46, and 61 µg/L). Boron concentrations were elevated across the study area (296–18,760 µg/L; mean 4,029 µg/L), with 141, 104, and 36 exceedances of the irrigation, domestic, and livestock guidelines respectively. Although wastewater-borne perborate and fertilisers are plausible contributors, the

widespread occurrence — including in remote areas — supports a predominantly geogenic origin from boron-bearing salts, clay minerals, or tourmaline in Quaternary sands, with a secondary contribution from marine aerosols [18,19]. Chromium concentrations reached 569 µg/L (mean 162 µg/L); 121 samples exceeded the domestic guideline (50 µg/L). This is consistent with geogenic origins previously reported for the UAE, including weathering of pyroxene, olivine, and chromite, and wind-transported Fe/Mn-oxide coatings with adsorbed Cr(VI) [20].

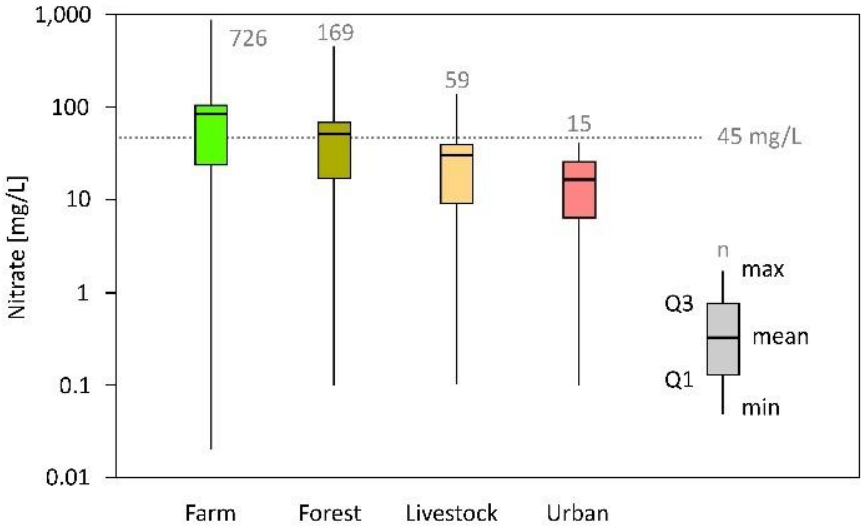


Fig. 14 Nitrate box plots for selected land-use classes. Whiskers represent the 5th–95th percentile range.

	TDS	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	SO_4^{2-}	HCO_3^{-}	F^{-}	Br^{-}	NO_3^{-}
TDS	1										
Ca^{2+}	0.87	1									
Mg^{2+}	0.92	0.76	1								
Na^{+}	0.98	0.79	0.88	1							
K^{+}	0.92	0.85	0.80	0.92	1						
Cl^{-}	0.99	0.84	0.90	0.98	0.92	1					
SO_4^{2-}	0.86	0.81	0.81	0.86	0.83	0.82	1				
HCO_3^{-}	-0.19	-0.24	-0.04	-0.18	-0.17	-0.20	-0.17	1			
F^{-}	-0.08	0.04	-0.16	-0.11	-0.05	-0.11	-0.06	-0.20	1		
Br^{-}	0.15	0.15	0.10	0.13	0.15	0.17	0.10	-0.13	0.18	1	
NO_3^{-}	0.21	0.34	0.13	0.18	0.28	0.19	0.29	-0.11	0.18	-0.05	1



Fig. 15 Pearson correlation matrix for selected water constituents.

Box plots for boron (Fig. 16a) confirmed a widespread distribution consistent with geogenic sourcing, while chromium (Fig. 16b) showed somewhat more variability between land-use classes. Selenium exceedances (108 samples above 10 µg/L for domestic use) were mainly encountered in saline groundwaters (Fig. 17), suggesting evaporative enrichment or salinity-promoted mobilisation from aquifer mineralogy. Molybdenum exceeded the irrigation and livestock guideline (10 µg/L) in 105 samples with a non-systematic distribution. A trace-element correlation matrix (Fig. 18) showed

mostly low coefficients, limiting source apportionment; the strongest correlation was between total and hexavalent chromium (R = 0.91), consistent with a Cr(VI)-dominated speciation of the anthropogenic and geogenic input.

Table 3 Statistical summary for the studied trace elements and number of exceedances (n > GLV) of EAD (2017) guideline values.

Parameter	Min	Mean	Max	Dom. use	n > GLV	Irr.	n > GLV	Livestock	n>GLV
Aluminium [µg/L]	b.d.l.	45.8	1,380			5,000	0	5,000	0
Antimony [µg/L]	b.d.l.	0.1	17.1	3	1				
Arsenic [µg/L]	b.d.l.	3.4	61.2	18	3	100	0	25	3
Boron [µg/L]	296	4,029	18,760	2,400	104	500	141	5,000	36
Cadmium [µg/L]	b.d.l.	41.3	3,666	2	3	5.1	2	10	2
Chromium [µg/L]	b.d.l.	162	569	50	121	1,000	0		
Copper [µg/L]	b.d.l.	1.2	36.7	1,000	0	200	0	400	0
Iron [µg/L]	b.d.l.	225	7,833			1,000	9	10,000	0
Lead [µg/L]	b.d.l.	0.1	2.5	10	0	200	0	100	0
Manganese [µg/L]	b.d.l.	22.0	859			20	17	10,000	0
Molybdenum [µg/L]	b.d.l.	52.3	1,541			10	105	10	105
Nickel [µg/L]	b.d.l.	6.3	152	20	5	200	0	1,000	0
Selenium [µg/L]	b.d.l.	22.0	135	10	108	20	67	50	9
Strontium [µg/L]	1,087	18,046	87,547						
Uranium [µg/L]	b.d.l.	7.7	228						
Vanadium [µg/L]	b.d.l.	40.1	616			100	9		
Zinc [µg/L]	b.d.l.	28.9	569	3,000	0	1,000	0	20,000	0
Hexavalent Cr [µg/L]	b.d.l.	100	400						

n > GLV, number of cases exceeding the guideline value; b.d.l., below detection limit.

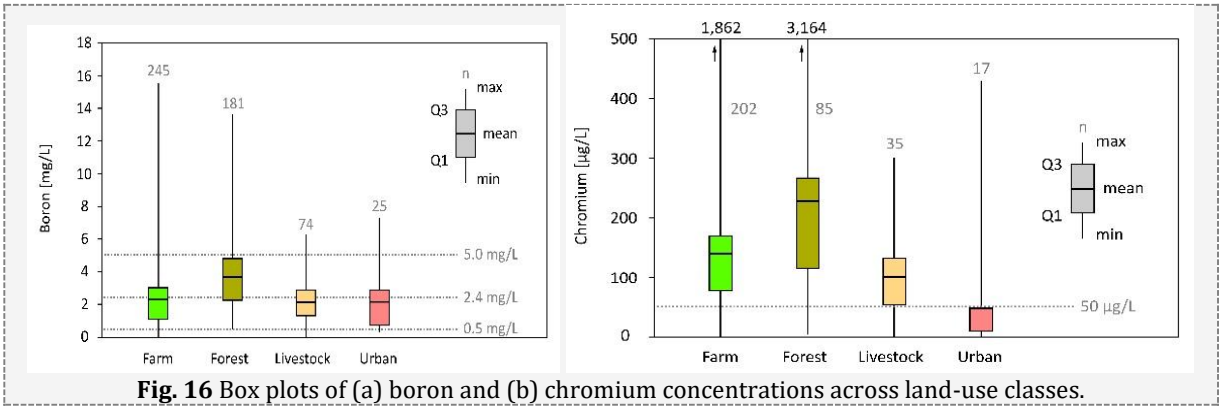


Fig. 16 Box plots of (a) boron and (b) chromium concentrations across land-use classes.

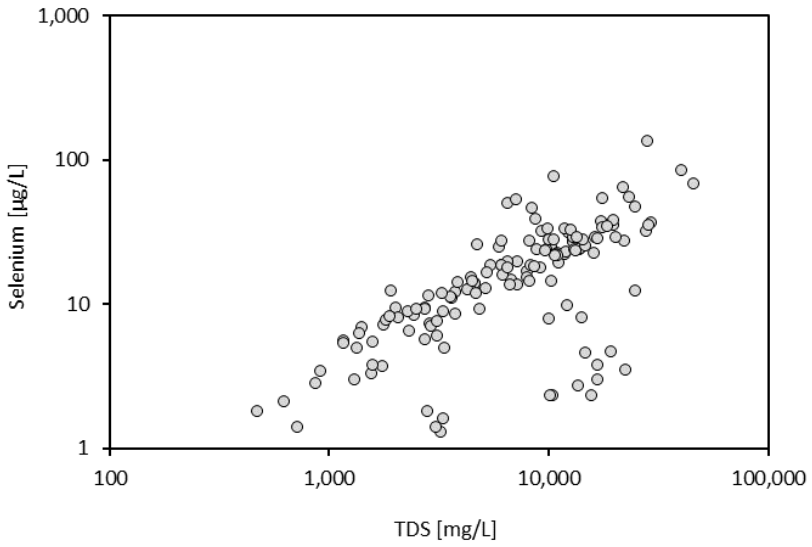


Fig. 17 Scatter plot showing the relation between selenium and total salinity.

	As	B	Ba	Cr (tot)	Cr (VI)	Fe	Li	Mo	Ni	Se	Sr	U	V
As	1												
B	0.03	1											
Ba	-0.16	-0.23	1										
Cr (tot)	0.03	0.44	-0.24	1									
Cr (VI)	0.02	0.28	-0.33	0.91	1								
Fe	-0.06	-0.06	-0.04	-0.13	-0.21	1							
Li	0.06	0.78	-0.27	0.34	0.23	-0.06	1						
Mo	0.52	0.30	-0.16	0.11	0.07	-0.05	0.29	1					
Ni	0.54	0.09	-0.04	-0.05	-0.11	0.05	0.15	0.62	1				
Se	-0.06	0.46	-0.12	0.22	0.15	-0.12	0.71	0.09	0.08	1			
Sr	-0.05	0.49	0.07	0.22	0.06	-0.08	0.56	0.11	0.04	0.59	1		
U	0.02	0.39	-0.16	-0.06	-0.11	-0.06	0.40	0.08	0.07	0.12	0.11	1	
V	0.65	0.11	-0.15	0.15	0.10	-0.07	0.10	0.03	0.49	0.01	0.03	0.11	1

Color legend

-1.0 -0.8 -0.6 -0.4 -0.2 0 0.2 0.4 0.6 0.8 1.0

strong... ...negative correlation weak... weak... ...positive correlation strong...

Fig. 18 Pearson correlation matrix for selected trace elements.

3.2 Anthropogenic impact assessment

3.2.1 Volatile organic compounds

Surrogate recoveries were acceptable for Toluene-d8 (83–120 %) and 4-Bromofluorobenzene (92–111 %), and initial concentrations were corrected accordingly. Despite a broad target list, all measured VOC concentrations were below the detection limit of 2 µg/L, indicating that VOCs are not a significant groundwater-quality concern at the Emirate scale.

3.2.2 Pesticides

Terphenyl-d14 surrogate recoveries ranged 85–111 %. The majority of targeted pesticides were below the detection limit of 0.002 mg/L. Seven pesticides were detected: phorate, methyl parathion, ronnel (fenchlorvos), chlorpyrifos, tetrachlorvinphos, aldrin, and 4,4'-DDD. Detections were concentrated in forestry and farm areas, with chlorpyrifos also occurring in an urban area in Al Ain. Most detected compounds are organophosphate insecticides, with aldrin and 4,4'-DDD being organochlorines. Except for chlorpyrifos, all detected pesticides have low leachability according to the

Groundwater Ubiquity Score [21] (Table 4), indicating that preferential-flow pathways and limited sorption in sandy, low-organic-carbon soils likely enhanced their transport to groundwater.

Table 4 Leachability classification of the detected pesticides, based on the Groundwater Ubiquity Score (GUS) after Gustafson [21].

Pesticide	Type	Substance group	GUS leaching potential
Phorate	Insecticide, acaricide, nematicide	Organophosphate	Low leachability
Methyl parathion	Insecticide	Organophosphate	Low leachability
Ronnel	Insecticide, veterinary	Organophosphate	Not available
Chlorpyrifos	Insecticide	Organophosphate	High leachability
Tetrachlorvinphos	Insecticide, acaricide, veterinary	Organophosphate	Low leachability
Aldrin	Insecticide	Organochlorine	Low leachability
4,4'-DDD	Insecticide, metabolite	Organochlorine	Low leachability

3.2.3 Pharmaceuticals

Carbamazepine, ibuprofen, and diclofenac were below the detection limit of 10 ng/L in all samples. Amidotrizoic acid — an iodinated X-ray contrast agent that is highly persistent in the subsurface — was detected in five wells: 24 ng/L (farm borehole), 27 ng/L (forestry borehole), 31 ng/L (urban borehole), 82 ng/L (urban borehole), and 172 ng/L (urban dug well) (Fig. 19). Two of these wells also showed elevated total coliforms and enterococci. The highest concentration was associated with a dug well, highlighting the particular vulnerability of shallow dug-well constructions to near-surface anthropogenic sources.

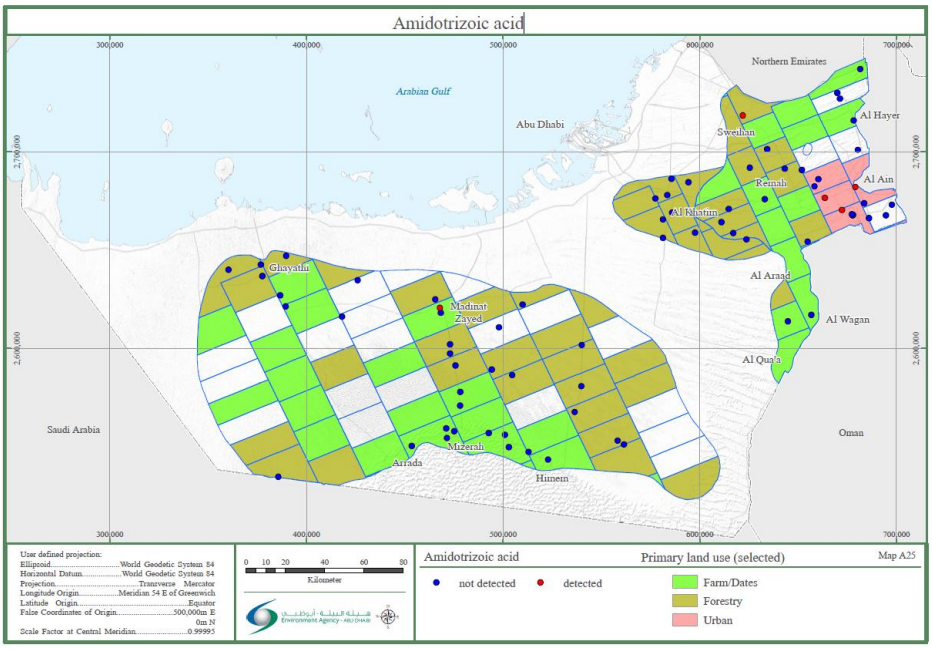


Fig. 19 Spatial distribution of amidotrizoic acid concentrations in the study area.

3.2.4 Microbiology

Microbiological QA/QC included field blanks (all negative) and duplicate analyses (excellent agreement). All *E. coli* tests were negative, but total coliforms, faecal coliforms, and enterococci were detected in 19 wells (Fig. 20, Fig. 21). Most contaminated wells were in forestry and farm areas, with

some in livestock and urban settings. Ten of the nineteen contaminated wells were dug wells, again pointing to the susceptibility of this construction type.

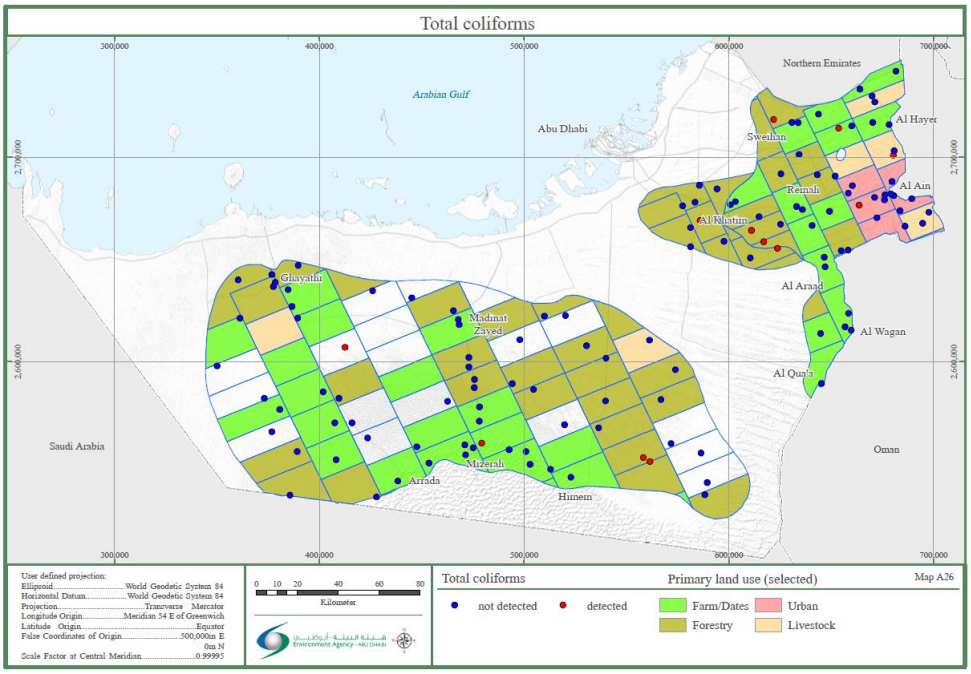


Fig. 20 Spatial distribution of total coliform detections.

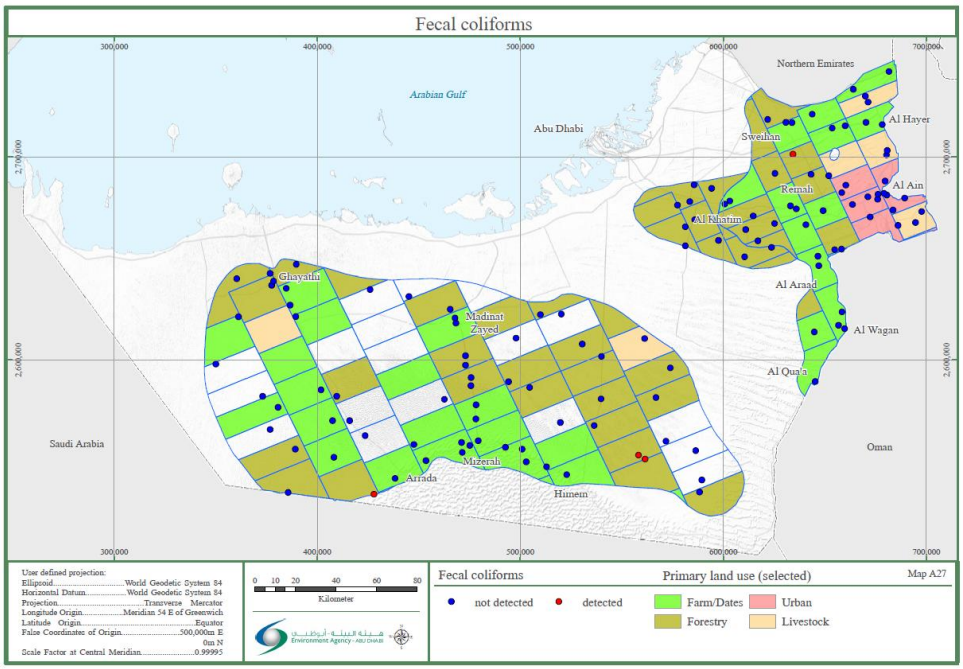


Fig. 21 Spatial distribution of faecal coliform detections.

3.2.5 Dissolved gases

Dissolved-gas results were largely unremarkable. Oxygen concentrations were in the low-single-digit mg/L range, methane was mostly below detection (maximum 9 µg/L), and nitrogen ranged from below detection to 48 µg/L. All CFC and SF_6 concentrations were below the detection limit of 0.25 pmol/L, consistent with limited modern recharge.

3.3 Environmental isotopes

3.3.1 Deuterium and oxygen-18

Stable water isotopes (δ^2H, $\delta^{18}O$) are conservative tracers unaffected by sorption or radioactive decay, and their fractionation during phase changes provides fingerprints of hydrological processes [22]. Isotope ratios are reported in per-mil notation (‰) relative to Vienna Standard Mean Ocean Water (V-SMOW). For the regional reference, IAEA GNIP data from Bahrain (Local Meteoric Water Line, LMWL: $\delta^2H = 5.48 \cdot \delta^{18}O + 11.2$ ‰; precipitation-weighted mean $\delta^2H = 7.5$ ‰, $\delta^{18}O = 0.69$ ‰) were used, with additional IAEA data for UAE rainfall showing good agreement (Fig. 22).

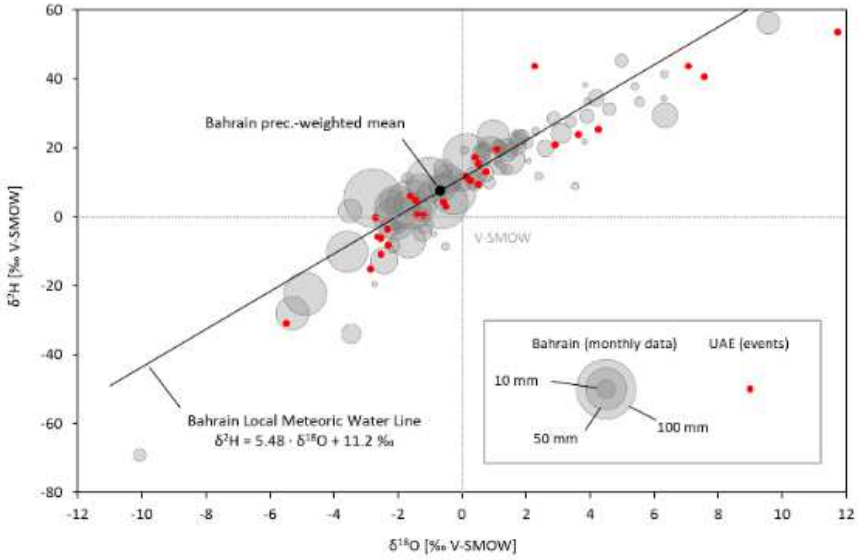


Fig. 22 Stable-isotope signatures of precipitation in Bahrain and the UAE.

Groundwater δ^2H (−11.6 to 10.5 ‰) and $\delta^{18}O$ (−2.09 to 4.43 ‰) showed moderate spread relative to precipitation data. The dual-isotope plot (Fig. 23) revealed two distinct groundwater lines for the Eastern and Western study areas, each with a slope of ~3 and a clear offset from the Bahrain LMWL. Eastern-area waters are isotopically depleted, while Western-area samples are enriched in ^{18}O. The offset is consistent with a combination of palaeoclimate and altitude effects [12,13], and the shallow slope indicates secondary evaporation prior to recharge, from shallow groundwater, or during irrigation. The line-conditioned excess (lc-excess = $\delta^2H - 5.48 \cdot \delta^{18}O - 11.2$) decreases with increasing TDS in both regions (Fig. 24), supporting the secondary-evaporation hypothesis for samples from farm and forestry wells.

3.3.2 Tritium

Tritium (^3H) is a radioactive isotope with a half-life of 12.32 years, reported in Tritium Units (1 TU = 0.118 Bq/L). Regional precipitation currently carries ~4–6 TU [22]. Assuming a detection limit of 0.6 TU, a modern-recharge component of ≥10 % is detectable. Most samples had ^3H concentrations below 0.6 TU, but 35 samples contained between trace levels and ~5.2 TU, with positive detections in both the Eastern (higher elevations) and Western (dune) areas, indicating that some modern recharge reaches the aquifers (Fig. 25, Fig. 26). The occurrence of detectable ^3H across a wide salinity range implies that young recharge mixes into both low- and high-TDS groundwater rather than forming a discrete young freshwater body.

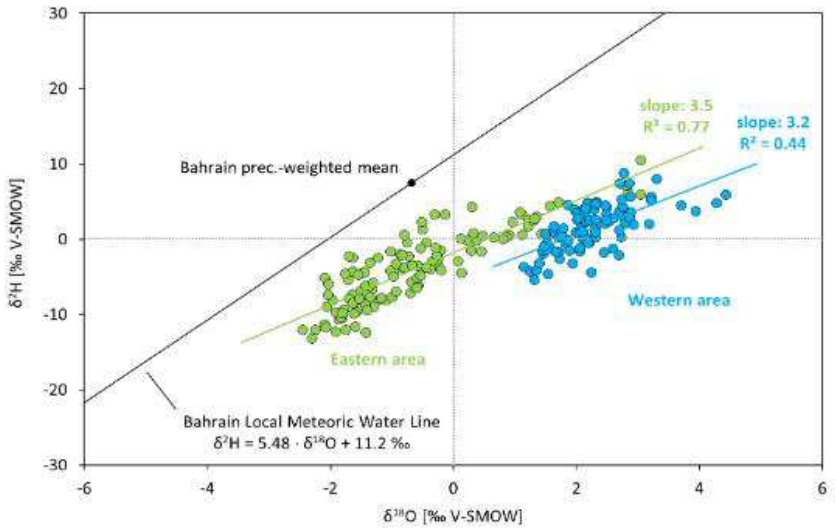


Fig. 23 Relation between δ^2H and $\delta^{18}O$ in the analysed groundwater samples relative to the Bahrain LMWL.

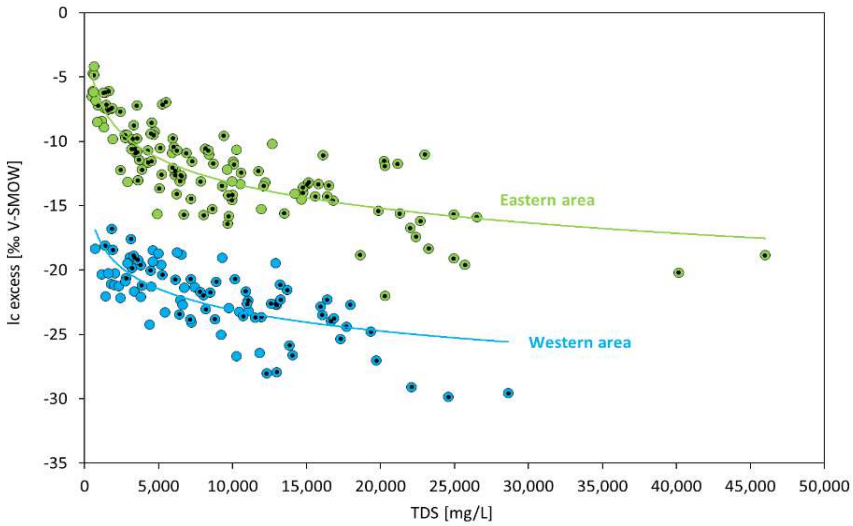


Fig. 24 Relation between the lc-excess and the corresponding TDS value.

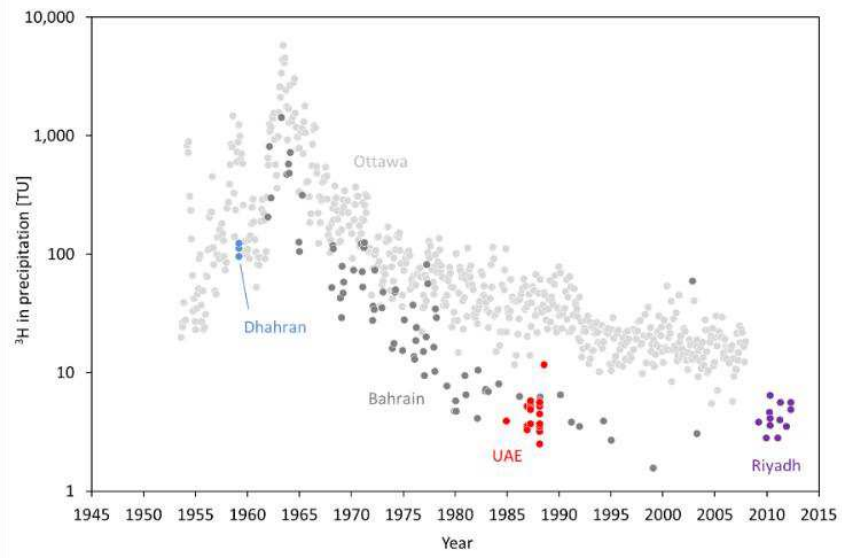


Fig. 25 Temporal development of ^3H concentrations in regional precipitation.

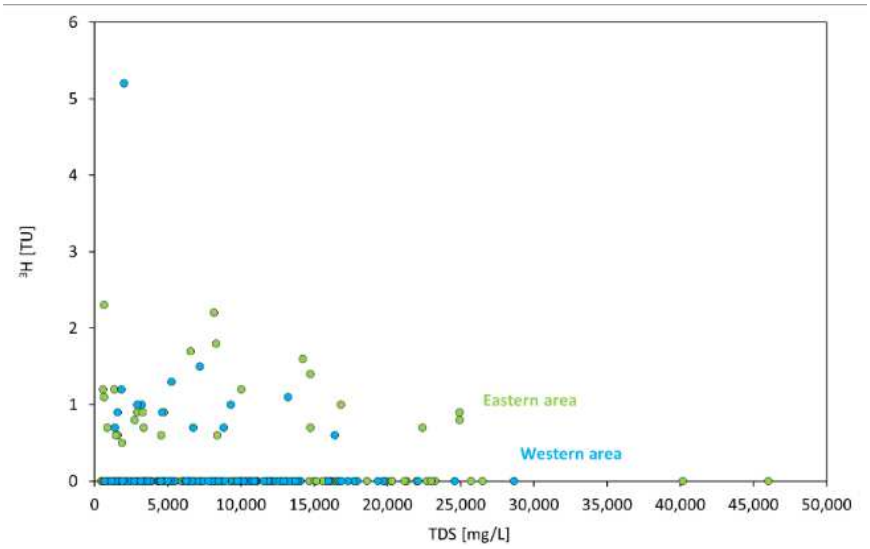


Fig. 26 Relation between ^{3}H and the corresponding salinity.

Samples with detectable ^{3}H were screened for modern-recharge indicators. Nitrate concentrations in this subset ranged from below detection to 217 mg/L (mean 54 mg/L), with six samples exceeding 100 mg/L. Pesticide and amidotrizoic-acid detections overlapped with ^{3}H-positive samples in several cases, and microbial contamination showed some overlap as well. Together, these observations demonstrate that where modern recharge occurs it can carry anthropogenic contaminants, highlighting local aquifer vulnerability.

3.3.3 Carbon isotopes

δ^{13}C (V-PDB) ranged from −12.9 to −3.4 ‰ (mean −8.2 ‰), indicating a significant contribution from carbonate-mineral dissolution, which is consistent with calcium and bicarbonate concentrations. ^{14}C activities ranged from 14.9 to 89.8 pmc (mean 44.5 pmc). Conventional (uncorrected) ages range from ~1,000 to ~20,000 years; application of the Pearson correction [23], taking into account the observed δ^{13}C and assuming a closed-system evolution, reduces the oldest apparent ages by 10–30 %, but still supports the interpretation of sub-modern to fossil groundwater for the majority of wells. These long residence times are consistent with the limited tritium detection, the offset of δ^2H–δ^{18}O from present-day precipitation, and the low recharge rates expected under current climatic conditions [12,24].

3.3.4 Nitrogen-15

Nitrate δ^{15}N (vs AIR) ranged from −8.4 to 29.5 ‰ (mean 6.4 ‰) (Fig. 27). Most values fell between 0 and 10 ‰, a range in which soil-derived, synthetic-fertiliser, and atmospheric sources overlap, limiting unambiguous source attribution. However, samples with nitrate > 45 mg/L were frequently associated with farming/forestry land use and with pesticide detection, indicating predominantly anthropogenic sources. Elevated δ^{15}N values in some urban wells may reflect septic-waste inputs, although denitrification — also known to enrich ^{15}N — cannot be excluded. Well ADD0961320 (Al Ain) showed high nitrite and low nitrate, a signature consistent with active denitrification. Incorporating δ^{18}O-NO_3^- in future campaigns would substantially improve source apportionment [25].

4 Groundwater uses and quality indices

The preceding sections evaluated individual parameters against use-specific guideline values. The present section provides an integrated assessment using water-quality indices (WQIs) for three potential uses: non-potable domestic use, irrigation, and livestock watering.

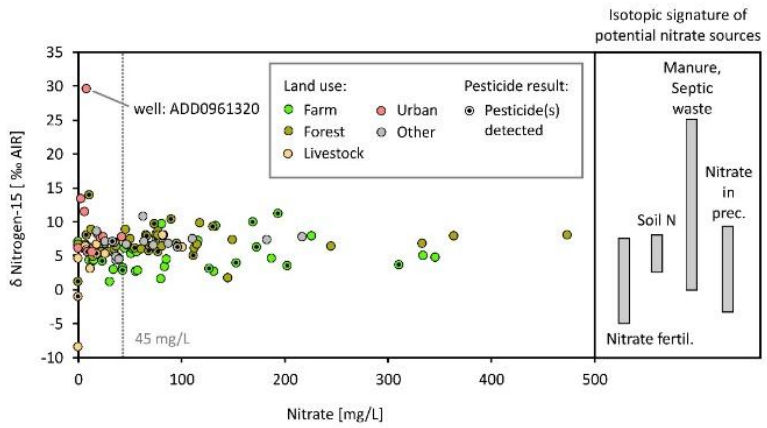


Fig. 27 Relation between $\delta^{15}N$ (in nitrate) and the nitrate concentration.

4.1 Domestic use

Non-potable domestic quality was evaluated using the Canadian Council of Ministers of the Environment (CCME) Water Quality Index, adapted to EAD (2017) guideline values [26]. The parameters considered were TDS (1,000 mg/L), chloride (200 mg/L), fluoride (0.4 mg/L), nitrate (45 mg/L), boron (2.4 mg/L), chromium (50 µg/L), and nickel (20 µg/L). This selection captures a summary parameter of overall quality (TDS) and the major and trace elements with the most frequent guideline exceedances, and allowed 212 additional analyses from the Well Inventory Project to be incorporated.

The CCME WQI combines three factors: the scope (F_1, percentage of failed variables); the frequency (F_2, percentage of failed tests); and the amplitude (F_3, the extent to which failed tests exceed their objective). F_3 is calculated from the normalised sum of excursions (nse) using an asymptotic function that scales the result between 0 and 100. The index itself is derived from:

$$WQI = 100 - \sqrt{(F_1^{\,2} + F_2^{\,2} + F_3^{\,2})} / 1.732$$

where the divisor 1.732 normalises the result to a 0–100 scale, with 100 representing the best quality. The CCME (2001) classification scheme (poor 0–44; marginal 45–64; fair 65–79; good 80–94; excellent 95–100) is reported for completeness, but absolute concentrations — particularly TDS — should always be considered alongside the index, as a critical single parameter can otherwise be masked by lower concentrations of the other constituents. The computed WQI values range from 4 to 100 (mean 36), reflecting the wide range of water quality encountered. The highest scores occur in the Eastern region close to the Oman border, where fresh waters dominate (Fig. 28). Kriged WQI maps should be interpreted with caution, as erratic concentration patterns — for example, arising from different well depths — can generate interpolation artefacts.

4.2 Irrigation

Irrigation suitability was assessed using two complementary approaches. First, the Wilcox classification [27] considers the combined salinity (EC) and sodium hazard (Sodium Adsorption Ratio, SAR). Most samples fell into the highest salinity (C4) and highest sodium (S4) classes (Fig. 29); boron was additionally represented semi-quantitatively via symbol size, illustrating that the bulk of samples exceeded the low EAD irrigation guideline of 0.5 mg/L.

Second, the Spandana et al. [28] rating approach was applied. This approach assigns each hazard category a weight and rates each parameter on a discrete scale (Table 5, Table 6). Each rating is multiplied by the corresponding weight, and the sub-scores (G_1–G_5) are summed to yield the composite WQI. The result is expressed either as a unit-less score or as a percentage of the maximum achievable score (45).

The resulting WQI percentage values ranged from 56 to 90 % (mean 67 %). As with the CCME approach, the highest scores occur in the Eastern region near higher-altitude recharge (Fig. 30). The SAR component is less of a practical concern in the study area because of the sandy soil textures, which limit the impact of sodium on soil structural properties.

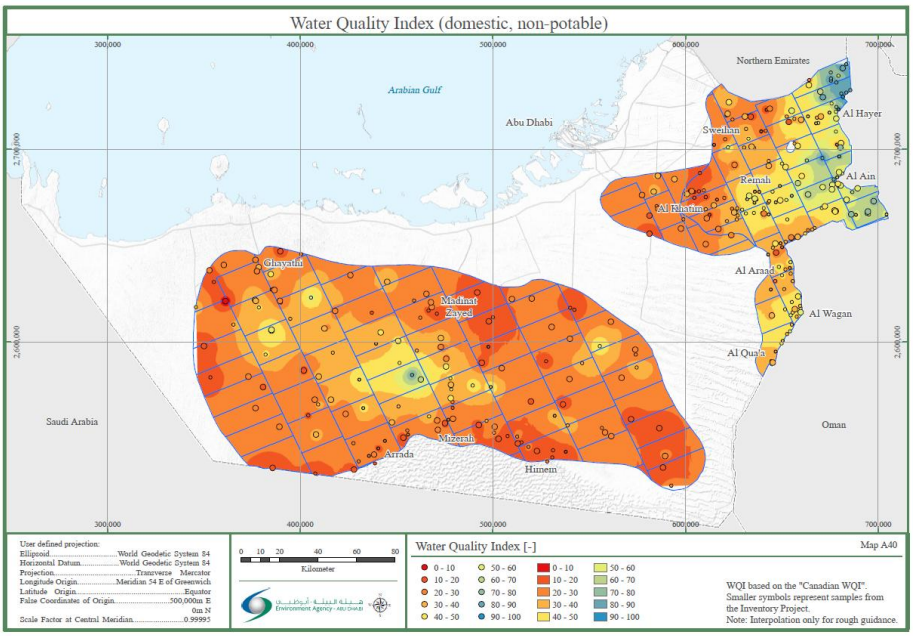


Fig. 28 Water quality index for domestic (non-potable) use.

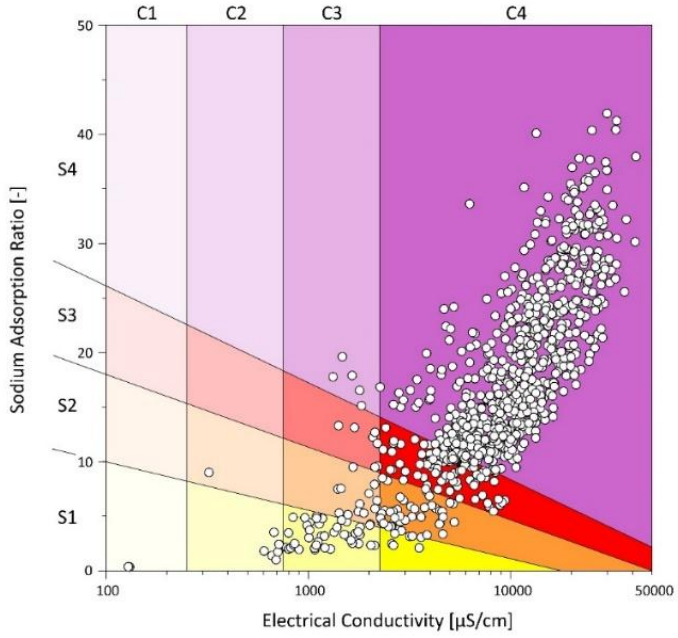


Fig. 29 Wilcox plot combining salinity (EC) and sodium hazard (SAR). Symbol size represents boron concentration.

Table 5 Rating scheme for the Spandana et al. [28] irrigation WQI approach.

Hazard	Weight	Parameter	Range	Rating	Suitability
Salinity hazard	5	EC [µS/cm]	< 700	3	high
			700–3,000	2	medium
			> 3,000	1	low
Infiltration hazard	4	see Table 6			
Specific ion toxicity	3	SAR [–]	< 3	3	high
			3–9	2	medium
			> 9	1	low
		B [mg/L]	< 0.7	3	high
			0.7–3	2	medium
			> 3	1	low
		Cl^- [mg/L]	< 140	3	high
			140–350	2	medium
			> 350	1	low
Trace-element toxicity	2	Fe [mg/L]	< 5	3	high
			5–20	2	medium
			> 20	1	low
Misc. effects	1	HCO_3^- [mg/L]	< 90	3	high
			90–500	2	medium
			> 500	1	low
		pH [–]	7–8	3	high
			6.5–7 & 8–8.5	2	medium
			< 6.5 or > 8.5	1	low

Table 6 Infiltration and permeability hazard rating based on the combined EC and SAR classes (Spandana et al. [28]).

EC / SAR ranges	SAR < 3	SAR 3–6	SAR 6–12	SAR 12–20	SAR > 20	Rating
High (rating 3)	EC > 700	> 1,200	> 1,900	> 2,900	> 5,000	3
Medium (rating 2)	200–700	300–1,200	500–1,900	1,300–2,900	2,900–5,000	2
Low (rating 1)	< 200	< 300	< 500	< 1,300	< 2,900	1

4.3 Livestock watering

Livestock watering quality was also evaluated with the CCME WQI approach, calculated separately for camel and sheep watering. The parameters considered for both animals were fluoride (2 mg/L), boron (5 mg/L), iron (10 mg/L), molybdenum (10 µg/L), nickel (1,000 µg/L), and zinc (20,000 µg/L). Salinity was represented by TDS (threshold 15,000 mg/L) for camels and by EC (threshold 11,000 µS/cm, after FAO [29]) for sheep. WQI values ranged between 35 and 100 for both animals, with means of 81 (camels) and 78 (sheep); the slightly lower scores for sheep reflect their stricter salinity threshold. The spatial patterns are similar for both animals, with the highest scores (80–100) in the East and

lower scores (40–80) elsewhere (Fig. 31, Fig. 32). A set of wells for inclusion in the future long-term monitoring programme is indicated in Fig. 33.

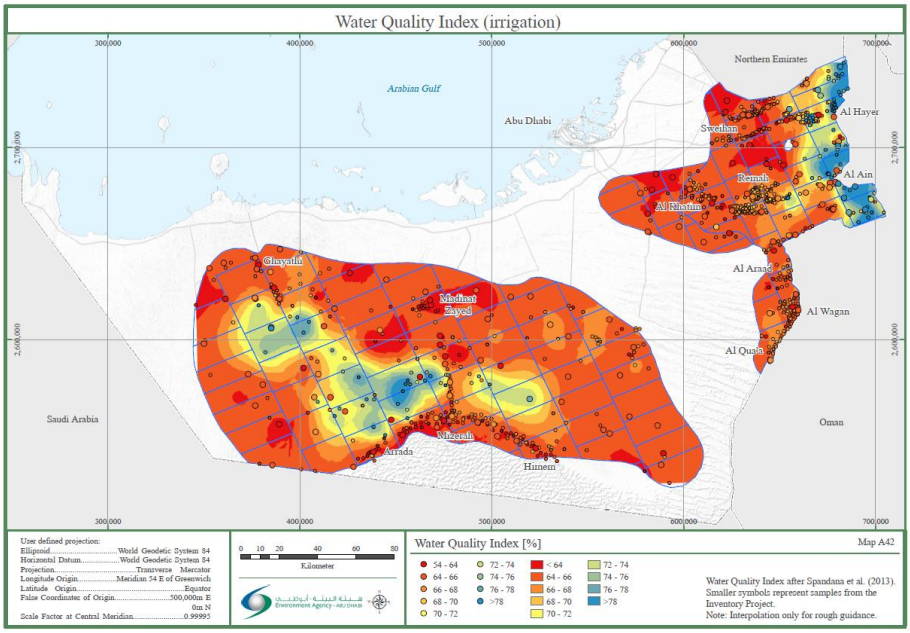


Fig. 30 Water quality index for irrigation use following Spandana et al. [28].

Table 7 Irrigation suitability classification based on the Spandana et al. [28] WQI.

WQI [–]	WQI [%]	Irrigation suitability
< 22	< 48	Low
22–37	48–82	Medium
> 37	> 82	High

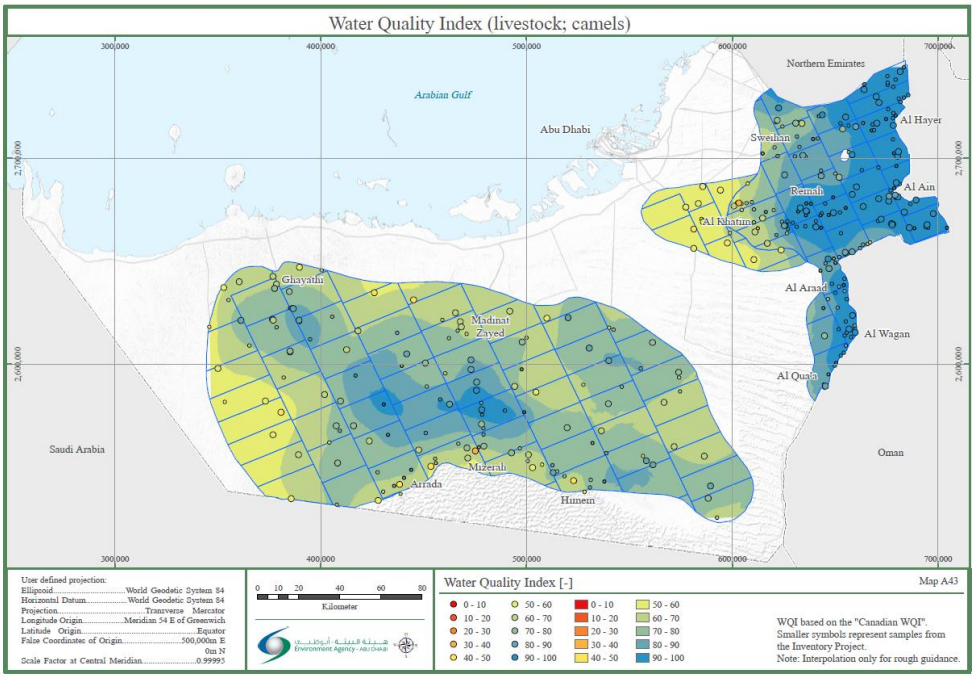


Fig. 31 Water quality index for livestock watering (camels).

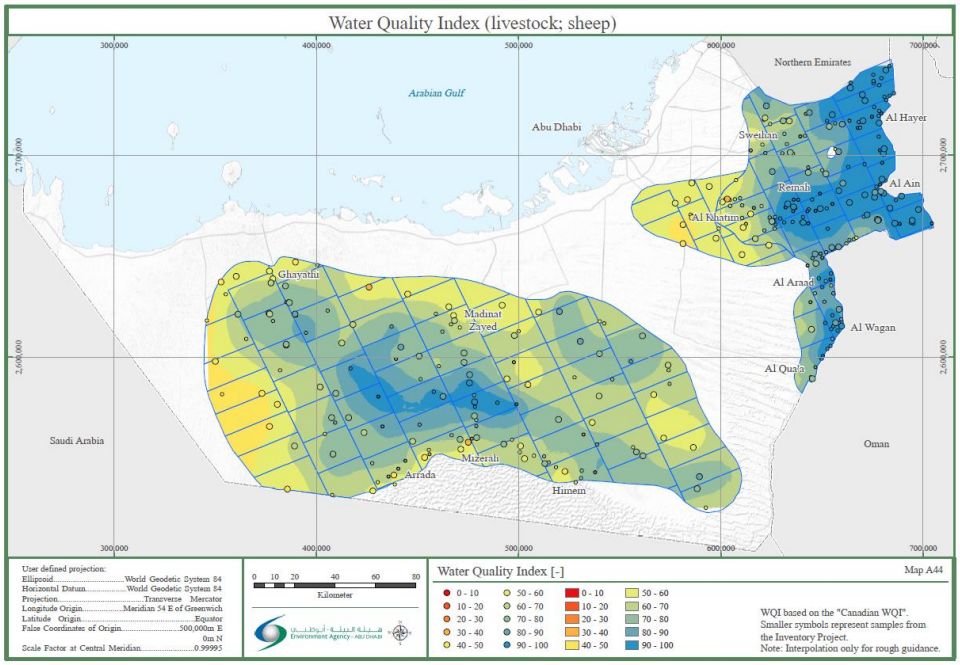


Fig. 32 Water quality index for livestock watering (sheep).

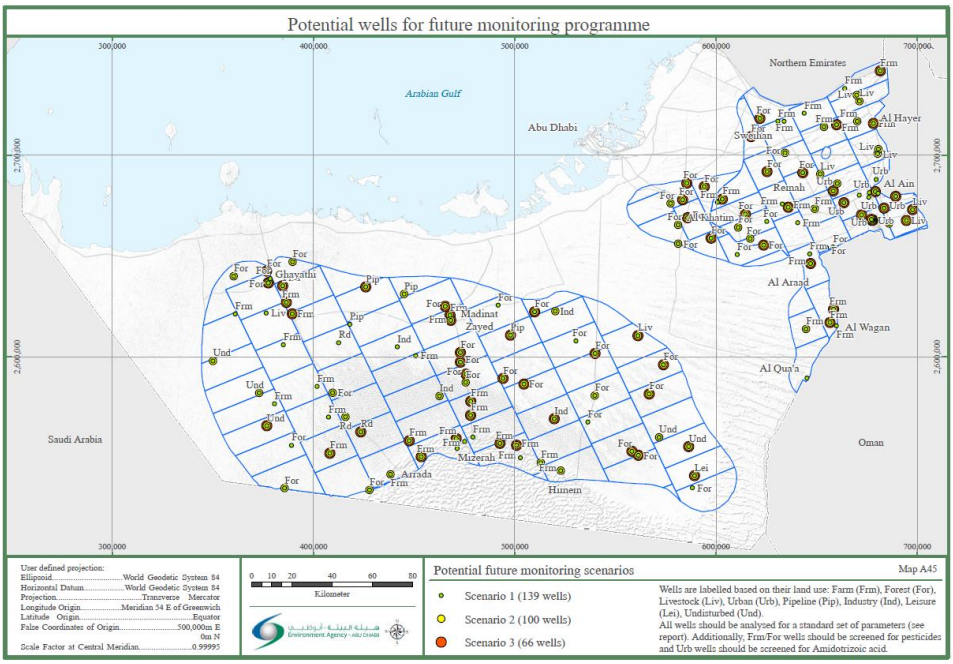


Fig. 33 Potential wells for future long-term monitoring.

5 Conclusions

This study establishes the first Emirate-wide, multi-parameter, isotopically-constrained baseline of groundwater quality for the usable-salinity domain of the Abu Dhabi Emirate. Salinity varies widely (TDS 473–46,000 mg/L), with freshwater occurring preferentially in the Eastern Region near the Oman border. The dominant water types (Na–Cl–SO_4 and Na–Ca–Cl–SO_4) reflect a combination of carbonate dissolution, evaporative concentration, and mixing with residual saline waters. Trace elements, in particular boron (141 exceedances of the irrigation guideline) and chromium (121 exceedances of the domestic guideline), are of concern, but their widespread spatial occurrence

supports predominantly geogenic origins from aquifer mineralogy and, for chromium, from wind-transported Fe/Mn-oxide coatings bearing adsorbed Cr(VI).

Localised anthropogenic inputs were demonstrated by pesticide detections in 37 wells, amidotrizoic acid in five wells, and microbiological contamination in 19 wells — with dug wells consistently shown to be the most vulnerable construction type. Environmental isotopes indicate that the Eastern and Western areas have distinct recharge histories and that most sampled groundwater is sub-modern to fossil (Pearson-corrected ^{14}C ages up to ~20 ka), with only localised evidence of modern recharge from tritium detections in 35 wells. Where modern recharge occurs, it co-occurs with anthropogenic indicators, highlighting aquifer vulnerability in those locations.

The computed use-specific Water Quality Indices reinforce the spatial pattern observed for individual parameters: the highest scores for domestic, irrigation, and livestock uses occur in the Eastern Region near the mountain-front recharge zone. The findings justify a tiered monitoring programme, in which routine monitoring of priority wells and parameters is supplemented by comprehensive Emirate-wide resurveys on a five-year cycle. Recommended priorities for future research are: (i) source apportionment of geogenic boron and chromium using $\delta^{11}B$ and $\delta^{53}Cr$; (ii) a dedicated precipitation-monitoring programme to establish a UAE Local Meteoric Water Line; (iii) extended pharmaceutical and personal-care-product screening; and (iv) targeted modelling of recharge and evaporation in land-use hotspots.

Declarations

Author contributions

O.S. – Conceptualisation, Investigation, Formal analysis, Writing – original draft; M.D. – Conceptualisation, Supervision, Writing – review & editing; K.A. – Investigation, Project administration; M.A. – Methodology, Data curation; M.A.-A. – Investigation; F.A. – Data curation; W.A. – Investigation; S.K. – Formal analysis; A.A. – Investigation; A.A.H. – Investigation; A.A.H. – Supervision. All authors read and approved the final manuscript.

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Data availability

The datasets generated and analysed during the current study are available from the corresponding author on reasonable request and subject to Environment Agency – Abu Dhabi data-sharing policies.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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